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Energy performances and life cycle assessment of an Italian wind farm

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Abstract

Renewable energy sources are often presented as "*clean*". A more correct definition is that they are "cleaner" than ones based on fossil fuel conversion. When the energy consumption and the environmental impacts related to the plant's life-cycle are considered, a more comprehensive assessment of these technologies can be carried out. This paper aims to evaluate the energy and the environmental performances of the electricity production of a wind farm. The impacts related to all the phases of the wind farm construction and operation have been compared to the environmental benefits due to the "green" electricity generation during its useful life. In other terms, the goal is to trace the ecoprofile of the production of 1 kWh of electricity.

A life cycle assessment (LCA) has been performed based on data related to an Italian wind farm: production and deliver of energy and raw materials, components manufacturing, transports, installation, maintenance, disassembly and disposal have been analysed. The attention focused to those life cycle steps generally neglected or not adequately investigated as installation, civil works and maintenance. The results can be assumed as representative of the Italian context and they can represent a further incentive to the diffusion of wind farms. In fact, the environmental performances of the wind farm have been compared to other power energy generation systems. The results showed a great environmental convenience of the inquired technology.

Keywords: Life cycle assessment (LCA); Wind farm

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1. Introduction

The employment of wind energy for the electricity generation is one of the most diffused technologies for the exploitation of renewable energy sources.

The European Commission aims to reach in the 2010 the target of a 12% of the overall primary energy consumption in the European Union (EU) and about 23.5% of electricity provided by renewable energy sources [1]. Wind energy is expected to give a great contribution with 40 GW of wind power installed in Europe, representing about 2.8% of the European electricity production.

In the last years the installation of wind farms has experienced an exponential growth: the cumulative wind power capacity in the EU raised to 34,205 MW at the end of 2004, up from 439 MW at the end of 1990 [2]. This growth is substantially aligned with the above cited European targets [1].

Having a cumulative capacity of 1125 MW in 2004, Italy is the fourth country as wind power capacity in Europe (just below Germany, Spain and Denmark). The Italian territory, especially in the southern regions, is characterized by climate and landscape very suitable for a further diffusion of this technology. The Italian Government foresees to double the installed capacity and to reach 2500 MW of wind turbines by the years 2008–2012 [3].

However, renewable energy sources are often presented as very 'clean' energy, not considering the environmental impacts related to their manufacture [4]. The production of the renewable plants, like every production process, entails a consumption of energy and natural resources as well as the release of pollutants [5].

The consideration of the energy requirement for the construction of energy supply systems is important in policy and planning (especially for comparative risk and sustainability assessments) or can be employed for the modelling of plant substitution, source switching and demand growth scenarios [6].

The environmental analyses of wind farms represent therefore a guide to address the large scale penetration of such technology, to identify the steps with the greatest impacts and with the largest improvements potentials.

Following a "traditional" life-cycle approach, this paper aims to evaluate the energy and the environmental performances of wind electricity production. This methodology has been applied to a case-study wind farm settled in Italy. The goal is to trace and assess the ecoprofile of electricity. The *Functional Unit* (FU)[1] is defined as 1 kWh of electricity generated and thereafter distributed to customers. The results of the study are useful for any Italian electrical company in order to improve the environmental management of wind farms and to minimise the impacts due to the construction of new plants or the dismantling of old ones.

1.1. The life cycle approach

Traditional environmental impact analyses generally focus on a restricted number of life cycle steps. For example, the impacts related to the electricity generation in conventional plants are generally identified with the impacts during the operation phase (i.e. the emissions due to the combustion of fossil fuels). This approach is very narrow because it gives only a "gate to gate" picture of the effective environmental performances of the product. Furthermore, in renewable energy plants generally the largest environmental impacts occur during the manufacture and installation steps.

The life cycle assessment (LCA) is a methodology able to investigate every direct and indirect impact throughout the life cycle steps of products or services. This approach is typically used to compare the environmental impacts for different products performing the same functions. The LCA is today well defined and also regulated by international standards of series ISO14040 [7–10]. The results of a life-cycle study applied to a renewable plant can be of great relevance for various scopes:

- to compare the performances of different systems or technologies (i.e. to compare the FU of a wind farm with the FU of an oil-fired plant or to compare the FU's from various typologies of wind turbines);
- to locate system's components or sub-processes responsible of the highest environmental impacts ("hot spots");
- to have useful information in order to reduce the environmental impacts and to improve the plant's performances;
- to show in the most appropriate way the advantages of the diffusion of a green market of the electricity.

[1] The FU is defined as the 'reference unit expressed as quantified performance of the product system' [7].

In particular, LCA can be the starting point to obtain an environmental product label[2] such as Type III environmental product declaration[3] (EPD) [13]. The EPD applied to renewable technologies represents a valid and effective way to spread environmental information to stakeholders and to increase the diffusion of such technologies.

The comparability of EPD results is granted by standardised rules, called product specific requirements (PSR), specifically complied for each product groups [14].

According to the EPD rules, the electricity production belongs to the "Electricity and District heating Generation" category [15]. The PSR explicitly establishes that "for some of the product systems in the product category the construction of the power facilities is the important part, (e.g. wind-, and solar energy) and hence it should be included as part of the input required for this product category". When performing a LCA it is a good practice to define proper system's boundaries and a cut-off threshold for impact assessment. The analysis should include a detail of all the materials and components employed throughout the life-cycle. Furthermore, the PSR establishes that any processes or activities that altogether do not contribute to more than 1% of the total environmental impact for any individual impact category may be omitted from the inventory analysis [15]. The system boundaries include:

- Refining of raw materials;
- Construction, operation and dismantling of energy conversion equipment as well as reinvestment throughout the technical lifetime;
- All relevant transport including transportation relating to maintenance;
- Management of wastes and residues generated as outputs throughout the production phase.

1.2. Environmental indexes

The evaluation of the energy and environmental performances of renewable plants should include a comparative assessment of impacts during the lifecycle and the energy saved during the operating time. Payback indexes answer to such purpose [16].

The payback time is an indicator generally used in economic studies to state the time to recover an initial investment. The energy payback time (E_{PT}) can be likewise defined as the time necessary for a wind farm to collect the energy (valued as primary) equivalent to that used during its life cycle; the emission payback time (EM_{PT}) is defined as the time during which the avoided emissions due to the employment of the wind farm are

[2]Following the classification of standard ISO14020, the product environmental labels are divided in three main groups [11]. Type I ecolabelling identifies products as being less harmful to the environment compared to other similar products, thanks to the compliance of minimum level of environmental performances and within the context of a third party verify. Type II is, instead, a self-declared environmental statement about the environmental performance of a product by the manufacturer itself. Type-III declaration, "a voluntary process by which an industrial sector or independent body develops an environmental declaration, including setting minimum requirements, selecting categories of parameters, defining the involvement of third parties and the format of external communications" [12].

[3]EPD scheme developed by the Swedish government represents a sort of "ecological identity card" annexed to products with the aim to synthesize their environmental performances evaluated across their whole life cycle. EPD gives information about the environmental quality of a product and allow the comparison between replaceable products.

equal to those released during the production, use and disposal of the renewable plant itself.

The payback ratio represents how many times the total energy produced by the plant exceeds the energy consumed during its life-time.

As the payback time, the "energy intensity" and the "CO_{2-eq} intensity" represent two indexes largely employed for the evaluation of plant's performance. They are defined as the ratio of the primary energy consumed, or CO_2 emitted for the construction, operation, and decommissioning, per unit of output of electrical energy over the lifetime of the device. These indexes are similar to the previous ones, except that the impacts are related to the effective electricity output and not to the primary saved energy.

Concerning wind turbines, the load factor represents another important evaluation index: it represents the average power divided by the peak power over a period and can be calculated as yearly ratio between the generated electricity and the maximum producible energy.

1.3. Environmental performances of wind farms

The European Commission, within the context of the Fifth European Environmental Action Programme, has financed a detailed LCA of renewable sources in 2004. The research project was titled (environmental and ecological life cycle inventories for present and future power systems in Europe) ECLIPSE [17–19]. This research has performed a life-cycle inventory regarding five technologies for the production of electricity, including wind farms. The inventory includes also the impacts due to the manufacture of wind turbines, nacelles and blades and these data can be assumed as representative of the European producers.

Lenzen and Munksgaard carried out an interesting survey of the environmental performances of wind farms all over the world [6]. The authors showed that "despite the fact that most modern wind turbines differ little over a wide range of power ratings with regard to their material consistency, there is a relatively large variation in energy and CO_2 intensities". About 70 studies regarding wind plants have been analysed, including various typologies and various sizes of wind turbines with a large power rating range from 0.3 to 3000 kW. The results can be assumed as reliable benchmark data of the wind farms performances. The results showed that:

- the energy intensity varies into the range 0.014–1 kWh_{used}/kWh_{el};
- the CO2 intensity varies into the range 7.9–123.7 g_{co_2eq}/kWh_{el};
- the load factors are enclosed among 7.6–50.4%.

These large variation ranges depend on the following reasons:

- turbine's power curves depend on their size: generally better performances belong to largest plants due to economies of scale ("bigger is better");
- average wind speed and frequency distribution are very site dependent;
- LCA assumptions, such as system boundaries, referring environmental database, expected lifetime, can have a strong influence on the results.

Table 1
Comparison of environmental performances of plants

Electrical generation plant	Global warming potential ($g_{CO_{2}eq}$/kWh)
Coal plants	900–1200
Diesel and heavy oil plants	780–900
Natural gas plants	400–500
Photovoltaic	50–100
Nuclear plants	15–50
Hydroelectric plants	15–40

In this study, the analysis has been conduced to a typical installation in Italy. This implies that the set of "geographical" factors influencing the results have been assumed accordingly.

It is also important to compare the performances of wind farm with the performances of other conventional and renewable electricity generation systems. Researchers estimate large variations of specific environmental burdens as shown in Table 1 [20–24]. On average, only hydropower plants have a lower global warming potential.

2. Case study: energy and environmental analysis of an Italian wind farm

The following sections show the results of a LCA applied to a representative case study: a wind farm belonging to an Italian electrical company.

Data regarding the installation, use and maintenance phases have been provided by the local electric company or have been directly collected during the construction of the plant or other similar neighbouring wind farms [25,26]. Data regarding the manufacturing of turbines and towers refers to average European data [17], provided that none of these components are manufacture in Italy. Specific environmental impacts of materials and energy sources refer either to national and international databases [27–29].

The chosen FU is a 1 kWh of generated electricity. However, in order to show the incidence of each life cycle step and to avoid the losts of information due to the aggregation procedures, results are presented as much disaggregated as possible. The first part of the study is a detailed analysis of each plant's component. Successively specific impacts per kWh of electricity have been assessed.

Being the results very dependent on data origin and specific assumptions, the study includes a sensitivity analysis which gives a picture of the influence of these factor on the results.

2.1. Wind farm: general framework

The case study wind farm is located in the South Italy (Sicily) and covers a global surface of 4.5 km^2. The area consists of a series of light-slope hills with an elevation between 850 and 937 m above sea level. The area does not include urban centres and encloses only a small number of rural buildings. The vegetation is constituted by wheat cultivations and spontaneous grass or small shrubs.

The plant includes 11 turbines of a nominal power of 660 kW each. The steel tower height is 55 m and the rotor diameter is about 50 m. Each tower is connected to a

transformer. The towers are installed on flat lay-bay and are firmly anchored with deep foundations.

The plant's layout has been defined with the following principles:

- the plant is adapted to natural hill shape in order to minimise excavations and soil's removal;
- the turbines are more than 100 m away from the existing buildings;
- the towers are located in order to avoid alterations of the wind flows and reciprocal interferences;
- the turbines are far from high traffic ways;
- the layout minimises the construction of new roads and paths.

The study has investigated the following life-cycle steps:

- manufacturing of wind turbines and other plant's components (cables, transformers, etc.);
- construction of building structures and auxiliary facilities (lay-bays, foundations, cable trenches, path connections, etc.);
- operation and maintenance;
- transports occurring during each phase;
- future plant's disposal.

2.2. Manufacturing of wind turbines

The analysis of the manufacturing step started from the detailed survey of system's components. The mass of used materials has been assessed on the basis of suppliers' technical reports and maintenance handbooks. The plant's components consist mainly of:

- Transformers enclosed into apposite building (surface: 9.90 m^2; volume: 24.3 m^3). Having no detail about transformer's materials, they are supposed to be entirely constituted by steel parts;
- Wind turbines. They are further constituted by:
  - tower: constituted by steel elements with an overall length of 55 m. steel parts are painted with anticorrosive paints;
  - nacelle: it includes all the generator's components enclosed inside a shelter of glass-reinforced plastic;
  - rotors: each rotor includes three blades of glass-reinforced plastic anchored to the nacelle.

The total masses of materials utilised during the wind generator manufacturing are synthesised in Table 2. Glass reinforced plastic is supposed to be a mixture composed by 76% of glass fibres and 24% of epoxy resin.

The tower components are mainly produced in North Europe and partially manufactured and assembled in Italy. The energy and environmental impacts due to manufacture have been estimated on the basis of average European data and refers to the ECLIPSE Project and to the supplier's environmental statements [30].

Table 2
Mass detail of a wind generator

Material	Mass (kg)
Steel	66,434
Cast iron	6001
Glass reinforced plastic	4950
Copper	924
Paints	389
Lubricant oils	111.2
Aluminium	85
PVC	65.2
Bronze[a]	5

[a]Bronze mass is supposed to be negligible.

The installation of wind towers is generally carried out by cranes and other typical construction machines and tools. Their fuel consumption has been directly measured during the building phase. Air emissions of machines engines have been accounted referring to an environmental database [28].

2.3. Building works

Building works includes all the structures and facilities produced "in situ" as support to the plant. They include:

- lay-bay: wind turbines are built on apposite flattened surfaces connected to roads and paths. Lay-bays are constituted by compacted crushed stone and limestone. A geotexile sheet of high density polyethylene (HDPE) is spread on the underlying layer;
- foundations: each wind generator is installed into a steel reinforced concrete foundation (square area of 110.25 m^2; maximum depth: 2.45 m). The first section of the tower is dipped on the foundation;
- electric cables: the turbines are connected to transformers and to the electrical grid with various cable typologies. The main line is constituted by an aluminium wire with a multi-layer protection of elastomer materials and an external PVC envelope;
- cable trenches: cables lie on seven different typologies of trenches (depth: 1.10 m; width: 0.6–1.10 m; global length: 3.3 km). Internal walls are reinforced with concrete and filled with sand and crushed stone. On the upper side trenches are covered with PVC tiles;
- paths and road connections: lay-bays are connected to each other with paths constituted by a compacted terrain based on a crushed stone ground. Even in this case, a geotexile sheet (HDPE) is spread on the road foundation. When necessary, roads and connection sides are protected by supporting walls realised in galvanised steel gabionades filled with crushed stone;
- transformer room.

The inventory data regarding the building works have been directly monitored during the building step. Construction materials come from regional producers; cables and plastic parts are imported from North Italy. The materials coming from excavations "in situ" are partially recovered for the construction of paths and cable trenches; other soils and gravels

Table 3
Building works—mass detail

Material	Foundations [kg]	Lay-bays [kg]	Cable trenches [kg]	Cables [kg]	Paths & roads [kg]	Main transformer room [kg]	Total [kg]
Aggregate quarrying	—	10,327,500	—	—	11,380,500	—	21,708,000
Local soils and stones	—	4,228,200	2,211,894	—	3,893,400	—	10,333,494
Steel	122,100	125	—	—	162	140	122,527
Polypropylene	—	48	—	—	67	—	115
HDPE	42	4084	—	—	7257	—	11,383
Polybutadiene	—	—	—	5141	—	—	5141
Aluminium	—	—	—	8289	—	—	8289
Copper	—	—	—	2893	—	—	2893
PVC	495	—	10,832	7605	—	—	18,932
Sand	—	—	2,802,279	—	—	—	2,802,279
Concrete	4,065,600	—	7680	—	—	24,000	4,097,280

are extracted from local quarries. The residual debris is delivered to the closest landfills. Table 3 shows the list of employed materials. During the construction two types of concrete are utilized: high resistance concrete (resistance 35 MPa) and low resistance concrete (15 MPa). The last one is mainly used for the bottom layers of the foundations.

The building contractor has provided information about energy consumption of excavators, compactors and other construction machines. Air emissions of machines are referred to the Italian environmental database [27].

2.4. Operation and maintenance cycles

The useful life of the wind farm is supposed to be 20 years long. The plant being totally computer-assisted, the ordinary operation requires negligible permanent personnel. The electrical company has however scheduled maintenance and control cycles. It was supposed a daily inspection during the first operation period and, successively, one inspection every 2–3 weeks. The personnel is transported by diesel car. It was supposed an overall consumption of about 7000 kg of diesel during the 20 years of useful life. Environmental impacts due to the transports have been referred to the Italian environmental database [27].

Ordinary maintenance cycles occur two/three times/year. They mainly imply lubrication, painting and substitution of spare parts as established by the maintenance handbooks.

Additional maintenance has been estimated according to common international practices and suggestions of the company's personnel. In particular, during the average useful life of a wind generator, it is supposed to substitute one blade and the 15% of generator's components.

2.5. Transports

The study includes the assessment of transports of hardware and components during each life-cycle steps. Transports occur by trains and trucks of various capacities. Rotor blades, nacelle parts, tower parts and wind turbines are produced in North Europe; they

are successively transported in order to be assembled and completed by a company in the South of Italy and finally delivered to the plant's site. Other plant's components (especially cables, plastics, steel products) are purchased by North Italy producers. Impacts of transports have been accounted referring to the "Boustead environmental database" [28].

2.6. Decommissioning phase

The plant's decommissioning is a life-cycle phase not completely predictable. No detailed data are actually available regarding Italian wind farms. A disposal scenario has been depicted on the basis of other European studies and researches [19].

It was supposed that the main components of the system would be delivered to various materials selection and recover plants (100–200 km far from the site). It has been assumed that the 90% of metals and the 20% of blades materials would be recycled. Other components are disposed to a landfill 100 km far from the site. Building works (paths, road, service building and foundations) will be not demolished nor decommissioned. Impacts related to disassembly are supposed to be equal to those assessed for the installation with the same employment of building machines.

3. Main LCA results

3.1. Energy analysis

The life-cycle inventory data have been processed in order to calculate the global environmental impacts for the whole life cycle of the wind farm (Fig. 1). The global energy requirement (GER) is 45.4 TJ_{Prim}. About 92% is related to manufacturing and installation, 6.4% to operation and maintenance and 1.7% to decommissioning.

Manufacturing is therefore the most energy intensive phase mainly because of the wind turbines construction (61%) and building works (32.5%). Transports during manufacturing have a low incidence (6.5%). Further details about turbines and building works are shown in Fig. 1.

The highest contribution is related to the employment of raw materials while the solely work for manufacture and installation processes play a secondary role.

A last consideration regards the feedstock[4] energy employment that amounts to 2.7 TJ_{Prim} (6% of the GER). Feedstock is mainly related to the employment of plastic materials into blades and cable lines.

3.2. Environmental analysis: wastes, air and water emissions

The assessed amounts of solid wastes, air and water emissions are reported in Table 4. The main impacts are the ones referred to the release of carbon dioxide (about $3,434,000\,\mathrm{kg}_{CO_2}$) and other air pollutants. Waste management is also critical being the wind farm responsible of the production of about 2500 kg of exhausted oils and lubricants and 37,300,000 kg of mineral wastes and building debris. Water pollutant emissions consist

[4]Feedstock is defined as "*heat of combustion of raw material inputs, which are not used as an energy source, to a product system*" [8]. The feedstock accounts the potential of materials (as wood or plastics) to deliver energy when they are burned with heat recovery after their useful life.

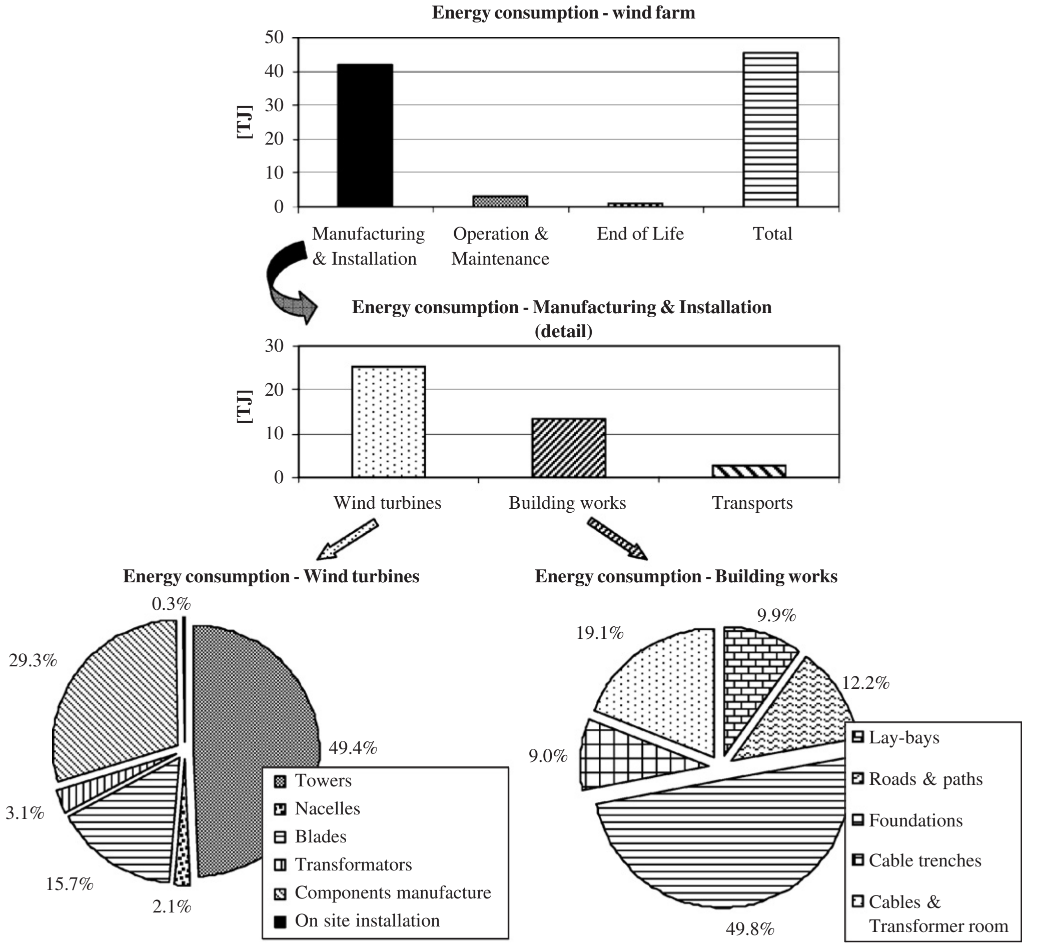

Fig. 1. Wind farm—detail of energy consumption.

mainly of moderate quantities of not dangerous chemical and biological substances related to the manufacturing phase.

Mineral wastes are due to excavations, quarries and terrain removal for building works, while oil wastes are mainly generated during maintenance cycles.

Also the environmental analysis shows a dominant incidence of the manufacturing phase mainly due to the material production.

3.3. Environmental analysis: other impacts

Other environmental impacts related to the wind farm life have been listed. They regard:

- soil use: the area directly occupied by each installed wind turbines is rather small (about $300\,m^2$). It is also necessary to include the area belonging to lay-bays and paths. Wind farm does not affect the adjacent areas that can be voted to agriculture and farming purposes;

Table 4
Wind farm—main environmental impacts

Air emissions			Water emissions			Wastes		
CO_2	3.43	[10^6 kg]	Suspended solids	2.3	[10^6 kg]	Mineral and debris	37.3	[10^6 kg]
CO	23.6	[10^3 kg]	Cl^-	20.6	[10^3 kg]	Ash	279.1	[10^3 kg]
SO_X	20.57	[10^3 kg]	Dissolved solids	6.1	[10^3 kg]	Oils and lubricants	2.5	[10^3 kg]
NO_X	13.50	[10^3 kg]	COD	1.0	[10^3 kg]			
Particulates	16.24	[10^3 kg]	$SO4^{2-}$	1.3	[10^3 kg]			
VOC	145.21	[kg]	BOD	40.1	[kg]			
N_2O	0.42	[kg]	AOX	0.9	[kg]			

- noise: from the electrical company database it shows that the noise level on the proximity of the basis of the tower is about 60–65 dB(A) but at the distance of 100 m the noise is lower than 55 dB(A);
- interferences with deep and surface waters: the plant has been built far from rivers and other water streams. The local water table is deep and it is not influenced by towers foundations;
- landscape alteration: actually the towers deeply influence and modify the landscape. However, it is not easy to quantify their visual impact. The area is, however, not characterised by any particular historical, archaeological or natural worth;
- effects on birds and wildlife: the plant does not insist along migratory routes of protected bird species. The interferences with wildlife are not supposed to be critical;
- electromagnetic noise: negligible, because of the absence of close sensible targets.

4. Ecoprofile of electricity

In order to refer the environmental impacts to the electricity output, it is worth to note the analysis to the plant's productivity.

The average yearly electricity production is 12,106 MWh/year. This value has been estimated according to the data recorded in the period January 2002–December 2003 and supposing all the wind turbines operative. This value is quite lower than the design assessment (30% higher). This is related to a short time data survey and to bad weather and wind conditions. Furthermore, in the first period only nine turbines were operative.

The eco-profile of 1 kWh of electricity has been calculated dividing the global plant's impacts by the global electricity production during the useful life, assuming the measured value for the calculation. Impacts have been synthesised by global indicators as suggested by the EPD [31]. Results are shown in Table 5.

However, the ecoprofile of electricity strongly depends on the plant's output. In fact, the previously cited yearly production value is quite lower than the design estimations (supposed about 30% higher). The actual load factor is 0.19 while the design figure was 0.3. This low value is probably related to the short time data survey and to adverse weather and wind conditions during the past years. The incidence of productivity will be further discussed in the next paragraphs.

Table 5
Ecoprofile of 1 kWh of electricity

Global warming potential	14.8	[$g_{CO_2^- eq}$/kWh]
Ozone depletion potential	6.59×10^{-7}	[$g_{CFC11eq}$/kWh]
Acidification	3.62×10^{-3}	[mol_{H^+eq}/kWh]
Photochemical ozone creation potential	1.61×10^{-2}	[$g_{C_2H_4eq}$/kWh]
Eutrophication	0.35	[g_{O_2eq}/kWh]
Inert wastes	154.2	[mg/kWh]
Special wastes	1.2	[mg/kWh]

Table 6
Incidence of embodied energy of raw materials into the *GER*

Steel components (steel, iron, pig iron)	49.3%
Construction materials (aggregate quarrying, sand, concrete)	14.1%
Composites (epoxy resin, glass fibres)	9.7%
Plastics (polybutadiene, polypropylene, PVC, HDPE)	6.3%
Copper	4.3%
Aluminium	3.4%
Others (lubricants, paints)	1.4%
Total	88.5%

5. Sensitivity analysis

Sensitivity analysis (SA) is a systematic procedure for estimating the effects on the outcome of a study of the chosen methods and data [8]. SA aims to identify ''hot spots'', namely the life cycle steps that are more burdensome to the environment [32].

SA can be applied assuming ranges of variation of input data which can be either arbitrary or representative of a given degree of uncertainty. SA gives a proof of the robustness of the results. Furthermore, SA is an important element of judgment for the corroboration or the refutation of the scientific hypotheses embedded into a model [16]. This is particularly critical when both model parameters and available data are affected by uncertainties (as occurs in LCAs). However, SA can also be used to direct the research priorities by focusing on the parameters that mostly determine the uncertainty of the model.

Concerning the wind farm case-study, the analysis of results showed that the largest energy demand and the main environmental impacts are due to the manufacturing of raw materials and systems components, which are responsible of about 90% of the GER (Table 6). In particular, the energy embodied into steel and iron parts represents about a half of the global energy requirements; worth of notes are also the contributes of construction materials (14% of GER) and reinforced plastics (10%). On the other side, the previous section has shown the critical role of plant's productivity on the electricity ecoprofile. The SA is focused on these categories.

Steel being the most important material concerning the GER figures, the inventory phase has been modified referring to another source of LCA data: the International Iron and Steel (IISI) studies [33]. Average data about ''hot dip galvanised steel'', ''hot rolled

coils'' and ''plate steel'' have been employed. In particular, the galvanised steel is supposed to be employed for the towers structure, steel coil and plate in the manufacturing of machineries, nacelle and transformers. The steel employed in the plant's building works (mainly wire rods and reinforcing bars) refers to IISI data for the building sectors. The age of data refers to the period 1999–2000. These ecoprofiles suggest that the global primary energy requirement of steel products approximately vary from 12.1 to 20.8 MJ/kg, while CO_2 emissions from 0.8 to 1.2 kg_{CO_2}/kg. These values are lower than the previous one (average impacts: 22.01 MJ/kg; 1.9 kg_{CO_2}/kg): this is imputable to greener production processes and to higher recycling rates (80–85%) of steel products. A further hypothesis regards the transformers. The new assumption deals with a composition of a 40% of copper components and 60% of steel parts.

According to these assumptions the plant's GER becomes 42.1 TJ (a reduction of 7% respect to the previous results) while the CO_2 emissions amounts to $2.75 \times 10^6\,kg_{CO_2}$ (about 20% lower).

The construction materials represent the most employed materials in the wind farm construction (see Table 2). Concrete, sand and, in particular, crushed stones are the dominant materials but their incidence in the plant's ecoprofile is moderate due to their relatively low specific impacts. However, small variations into their ecoprofile could cause sensible modifications into the environmental balance of the wind farm. The inventory data have been modified introducing the ecoprofile of these materials referred to [29]. Because of the new characteristics of construction materials, the environmental impacts arise of about a 10%. The largest incidence is related to the modifications of gravel and pebbles profiles.

A mix of epoxy resins and glass fibres mainly constitute the composites. Concerning the resins, the data source is reliable and can be considered as representative of the average European production [28]. A further investigation focused on other ecoprofiles of reinforced plastics employing glass fibres as well as other replaceable fibres (carbon and flax fibres) [34]. In particular, the use of carbon fibres would increase the energy consumption of about 12%, while a moderate reduction (−1%) could be obtained with the introduction of vegetable fibres.

The analysis has consequently shown that GER varies form 42.1 to 50.7 TJ, while the CO_2 emissions varies from 2.7×10^6 to $3.7 \times 10^6\,kg_{CO_2}$.

Regarding the plant's productivity, the measured data of electricity output have been lower than expected at the design stage. The company suggested that the start-up problems (only at the beginning of 2003 all the wind turbines became operative) and the bad climatic conditions in the 2003 influenced the energy performances. For these reasons, various scenarios of productivity have been supposed (Table 7):

- Scenario 1: Effective productivity in the 2002 (it encloses the worst conditions and the lowest productivity).
- Scenario 2: Effective production in the 2003.
- Scenario 3: Estimation on the basis of sampled data, supposing all the wind turbines correctly operating since the beginning of the wind farm installation (this scenario coincides with the estimation of section 4).
- Scenario 4: Productivity equal to the 80% of design estimations.
- Scenario 5: Productivity estimation at the design stage, on the basis of average wind conditions.

Table 7
Scenarios of electricity output

Yearly wind farm productivity [MWh/year]				
Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
10,494	11,384	12,106	13,120	16,400

Table 8
Reference electricity generation mix

	Electricity Italy [GEMIS, 2005]	Electricity Italy [ANPA, 2000]	Electricity Italy [Boustead, 2001]	Electricity average EU-25 [GEMIS, 2005]
[MJ_{Prim}/MJ]	2.56	2.87	3.04	3.02
[kg_{CO_2}/MJ]	0.15	0.19	0.16	0.13

Starting from the estimation of Table 6 it is possible to assess the primary energy saving and the saved emissions. These values can be obtained supposing that the wind farm is alternative to the traditional plants for the electricity production. A sensitivity analysis has been carried out about the electricity generation mix (Table 8). The Italian mix, as reported in Refs. [27–29], has been compared to the EU-25 average mix in the 2000 [29].

On the basis of productivity scenarios of Table 7 and the assumptions of electricity mix of Table 8, the primary energy saving during 20 years of operating time have been estimated in the range 90–180 TJ_{Prim}, while the saved CO_2 emissions are in the range $5 - 11 \times 10^6\,kg_{CO_2}$ (Fig. 2).

Data regarding the sensitivity analysis and assumptions regarding the productivity and the saved emissions have been employed for the estimation of the energy and the environmental indexes.

5.1. Payback indexes

Considering the variability of electricity production and of plant's ecoprofile, the energy intensity varies from 0.04 to 0.07 kWh_{Prim}/kWh_{el}, CO_2 intensity index varies from 8.8 to 18.5 g/kWh.

Regarding the payback indexes (Fig. 3), it is possible to assess that, even in worst conditions, after 1 year the energy consumption and greenhouse gases emissions are balanced.

These values are compatible with the reference ranges shown in Section 1.2. Furthermore, during its operating time, the primary energy output is equal to 40–80 times the energy globally consumed during its life-cycle (Fig. 3c).

Wind farm can be assumed as one of the most ‘‘environmental friendly’’ technology, also compared to other renewable energy sources.

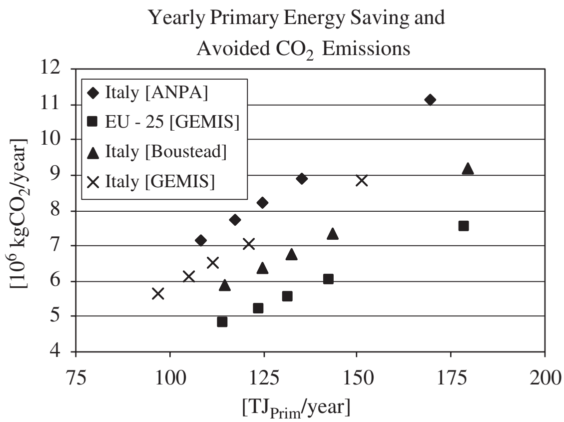

Fig. 2. Estimation of primary energy saving and saved emissions during the operating time.

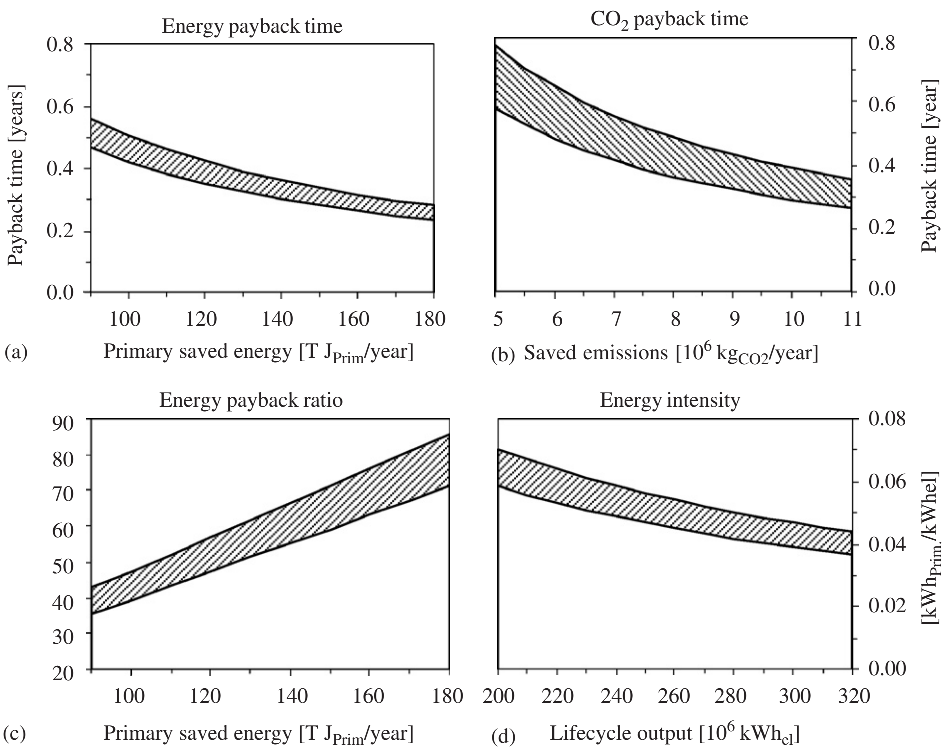

Fig. 3. Payback indexes.

6. Conclusions

The paper has described a LCA of an Italian wind farm. Manufacturing, installation, transports, maintenance, disassembly and disposal phases have been analysed.

The research shows that the largest environmental impacts caused by a wind farm are mainly due to the manufacturing of wind turbines and building works. These impacts principally consist of air emissions, inert solid wastes and small quantities of hazardous exhausted oils and lubricants. Other impacts are not significant.

The ecoprofile of the plant is strongly affected by the ecoprofiles of the raw materials (mainly, steel components, construction materials and composite materials) that together are responsible for about 70% of the global impacts. In particular, the use of recycled materials during the plant manufacture could decrease the total life-cycle environmental impacts.

The global energy requirement varies from 42.1 to 50.7 TJ, while the CO_2 emission varies from 2.7×10^6 to $3.7 \times 10^6\,kg_{CO_2}$.

Concerning the specific impacts per kWh of electricity, data are strongly influenced by the productivity estimations. However, the energy intensity varies from 0.04 to $0.07\,kWh_{Prim}/kWh_{el}$, CO_2 intensity index varies from 8.8 to 18.5 g/kWh. Payback indexes resulted lower than 1 year and the primary energy output is 40–80 times higher the energy globally consumed during its life-cycle.

These values are sensibly lower compared to the environmental burdens of fossil fuels fired plants and to other renewable energy sources.

The exploitation of wind energy and the growth of wind farms can therefore represent a useful strategy to achieve the Kyoto protocol agreements and to reduce the energy dependence for fossil fuels.

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